Further Details on Lead-Free Reflow Soldering of LEDs

Application Note

Abstract

The interaction between RoHS-compliant SMD components and lead-free processing continues to lead to complications, as the previous know-how worked out with tin-lead processes is only partly applicable to the new material system. In addition to providing general notes on the lead-free reflow process, this document will show and explain in detail the crucial parameters for creating a soldering profile. To counteract uncertainties and the problems that result, it will also present a detailed recommendation for the processing of SMD light emitting diodes (LEDs).
Particular attention will be paid to the prevention of heat-induced damage to the SMD components and printed circuit board substrates that are used.

Introduction

Reflow soldering has established itself as a valid industry standard worldwide for the contacting and mounting of SMD components.

The essential process step in reflow soldering is always the concerted melting of a previously applied solder deposit (paste) in a through-type oven. Technically, the most consistent possible heating of a board is achieved by forced convection of hot air or nitrogen.
Since the RoHS directive came into effect in June 2006, only lead-free compounds (usually SnAgCu) have been used as solder material, replacing the previous PbSn alloys. As the previous expertise for the lead-containing solder is not directly transferable to the new material system, processing problems continue to occur with regard to the components.
Due to the higher melting point of lead-free alloys, simply switching to a new solder and increasing the relevant process temperature is not procedurally sufficient and does not produce the desired results.
Due to the conditional reduction of the process window for the lead-free solder materials, increased attention must be paid to the soldering equipment (e.g. oven design) and the actual process control. The application-specific and component-specific characteristics must also be taken into account.

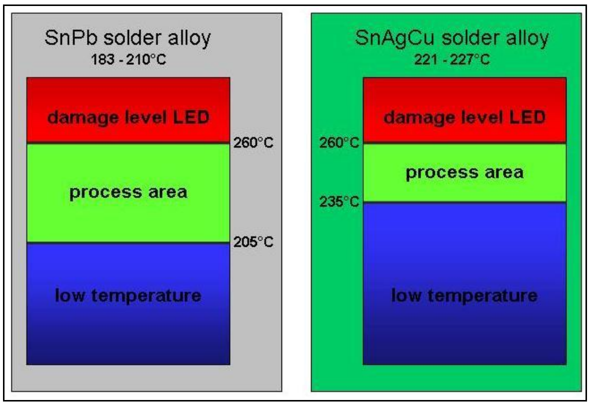


Figure 1: Comparison of the process window, tin-lead vs. lead-free solder

Without precise fine-tuning the risk increases that the components will be damaged due to thermal stress.
Ultimately, for lead-free soldering a compromise must be found between the reduction of the required amount of heat to the minimum necessary and an efficient reflow process in which the necessary amount of heat is transmitted in a short time and at minimum temperature difference.

OSRAM
Opto Semiconductors

JEDEC J-STD 020D.01

("Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices", [1])

The JEDEC standard J-STD 020D.01 is the primary basis and reference point for the reflow soldering of SMDs with plastic or other moisture-permeable housings, a category to which LEDs also belong.

This includes general requirements and limits for the classification of SMD components with regard to their behavior in humidity (MSL - moisture sensitivity level) and the resulting measures for packaging, storage, and handling.
This is to ensure that damage is avoided in production using reflow soldering.

The most important point in terms of reflow soldering is to determine the maximum temperature resistance as a function of housing thickness and the volume of the components (Table 1).
The classification temperature T_C, measured on the top of the component, represents the housing temperature up to which the component has usually been certified by the manufacturer and up to which its temperature resistance and processability are ensured at the specified moisture sensitivity.

The housing temperature is defined as "package peak temperature" (PPT), or also often as "package reflow temperature". Because of the term "reflow", it is often also mistakenly assumed that the temperature refers to the process of creating the solder connection, i.e. the solder joint temperature.

The values MSL and PPT are used only for product characterization, and provide information regarding the robustness of semiconductor components for reflow soldering, or set the time window for how long the components may be exposed to a controlled environment before an additional drying process is necessary prior to processing (soldering).

With regard to processing, the JEDEC standard contains relevant key data and generally applicable limits (Table 2) and also provides a general, basic temperature-time characteristic (= soldering profile) for the reflow soldering process (Figure 2).

Profile property	Lead-free processing
Preheat/soak Temperature min (T_{smin}) Temperature max (T_{smax}) Time (t_s) from (T_{smin} to T_{smax})	 150 °C 200 °C 60-120 seconds
Ramp-up rate (T_L to T_p)	3 °C/second max.
Liquidus temperature (T_L) Time (t_L) maintained above T_L	217 °C 60-150 seconds
Peak package body temperature (T_p) *	For users, T_p must not exceed the classification temp For suppliers, T_p must equal or exceed the classification temp
Time (t_p)** within 5 °C of the specified classification temperature (T_c)	30* seconds
Ramp-down rate (T_p to T_L)	6 °C/second max.
Time 25 °C to peak temperature	8 minutes max.

*** Tolerance for peak profile temperature (T_p) is defined as a supplier minimum and a user maximum.**
**** Tolerance for time at peak profile temperature (tP) is defined as a supplier minimum and a user maximum**

Table 2: Relevant key data and limits for the reflow soldering profile

Housing thickness	Volume in mm³ < 350	Volume in mm³ 350 - 2000	Volume in mm³ > 2000
< 1.6 mm	**260 °C**	**260 °C**	**260 °C**
1.6 mm – 2.5 mm	**260 °C**	**250 °C**	**245 °C**
> 2.5 mm	**250 °C**	**245 °C**	**245 °C**

Table 1: Maximum temperature resistance T_C as a function of housing thickness and volume for lead-free processing (J-STD 020D.01)

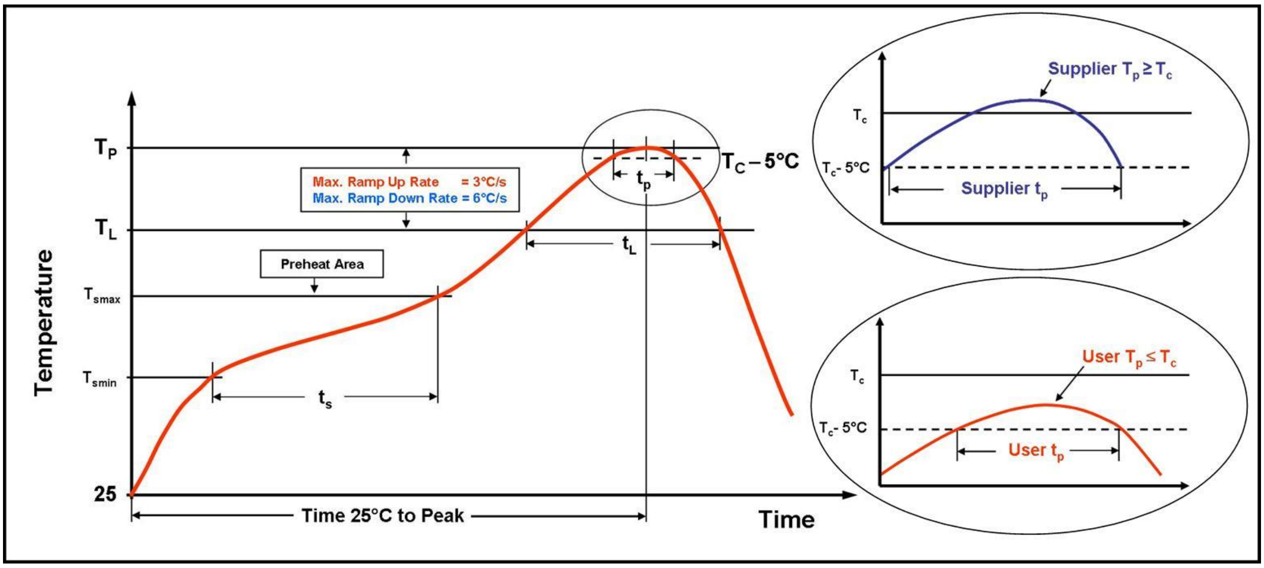


Figure 2: General classification profile for reflow soldering according to J-STD 020D,01

This shows once again how the housing temperature is to be observed and used, on the one hand, for manufacturers as a limit in qualification, and on the other hand, for customers during processing.

The JEDEC standard additionally stipulates that all temperatures refer to the center of the package, and that measurements should be implemented on the housing surface areas that face upward during soldering ("live bug").

Reflow oven

The focus and significant influence factor of each reflow process is the oven used to melt the solder paste.

The introduction of the RoHS directive and the associated higher operating temperatures mean that increasing demands are made on modern reflow ovens, including in terms of new soldering processes to be evaluated.

The focus is on precisely adjustable temperature profiles, precise repeatability, and minimum energy requirements, while providing easy handling and highest throughput.

The most important goal in this context is the stability and uniformity of the heat transfer to minimize the temperature difference (ΔT) on the board to be soldered.

In modern convection reflow ovens, the heat is transmitted by flowing air or nitrogen, which is heated or cooled depending on the zone.

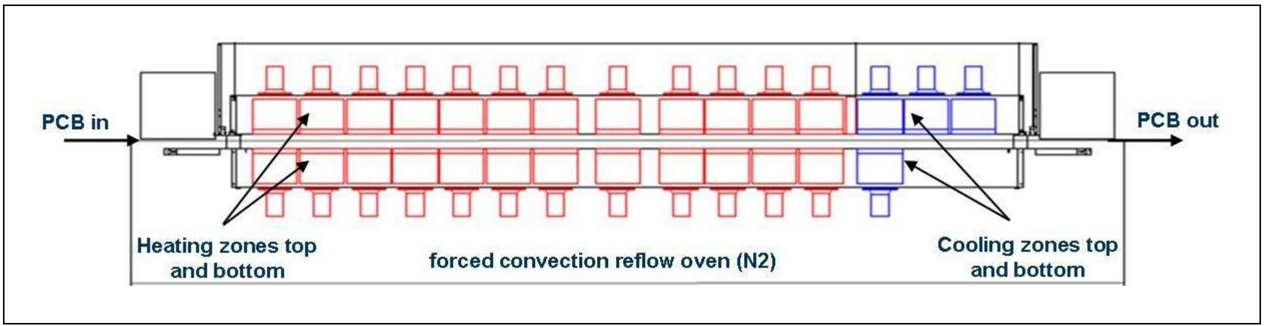


Figure 3: Schematic representation of the reflow oven used by OSRAM Opto Semiconductors with 12 heating and 3 cooling zones

The effective energy transfer to the board is therefore determined by the flow rate of the gas. Due to the different dimensions and mass of the components, it is therefore essential to design the flow rate so that it may be adjusted to avoid an offset or components being blown away.
The stability of the process zones, even with different oven loading, is obtained through the separation of the individual heating zones, through the use of powerful heating elements, and by a precise and fast temperature control.

To ensure a stable soldering process, a reflow oven should have the following characteristics:

- Separately controlled heating zones (top and bottom)
- Variable profile setting through as many heating zones as possible
- No mutual influence on temperature and flow from zone to zone.
- Controlled flow and flow rate
- Same temperature and flow properties across the entire process
- No shadow effects
- No offsetting of components
- Rapid heating-up times
- Separately controllable cooling zones, with top and bottom cooling

Temperature profile

To create an ideal temperature profile for an electronic module, all influencing factors involved (for example, solder paste, thermal mass, number and size of components, board design, material and construction of the printed circuit board, soldering oven) should be known and taken into account (q.v. Application note "Measuring of the Temperature Profile during the Reflow Solder Process).

The recommendations of the solder paste manufacturer should be used as a starting point for profiling. Here the relevant parameters (or limits) are generally already specified for which the manufacturer expects an optimum result for the solder paste that is used.
Information on the solderability of the printed circuit board used is usually not available so that rough assessments for profile creation can only be based on the material (FR4 or IMS), design (number of layers), and the wetting properties of the surfaces.
Particular attention should be given in the profiling to the specified maximum load limits of the SMD components. Generally, the components' manufacturers refer to the relevant standards such as JEDEC J-STD 020, J-STD 075, and IEC 60068-2-58.

As a summary of the available information, the following classification of the reflow profile can be defined in four phases (Figure 5). An understanding of these four phases is of essential importance in creating this.

P1 Pre-heat zone

In the first step, the circuit board, the SMD components, and the solder are heated up to a certain temperature (depending on the solder paste used, between 120 °C and 150 °C), at which the solvent and moisture contained in the solder evaporate slowly. The heating gradient should not exceed 2 °C/s. Faster heating can, on the one hand, cause a reduction of the contour stability of the solder paste and solder balling, and on the other hand, temperature gradients greater than or equal to 3 °C/s can damage the components and substrates. Errors such as cracking and delamination can result.

P2 Soak zone

The soak zone, also known as solder paste dry zone or activation zone, is necessary to stabilize the temperature as evenly as possible across the whole board.

At the same time, this zone also serves to activate the flux, i.e. the flux changes into a liquid state and cleans the surfaces to be soldered.

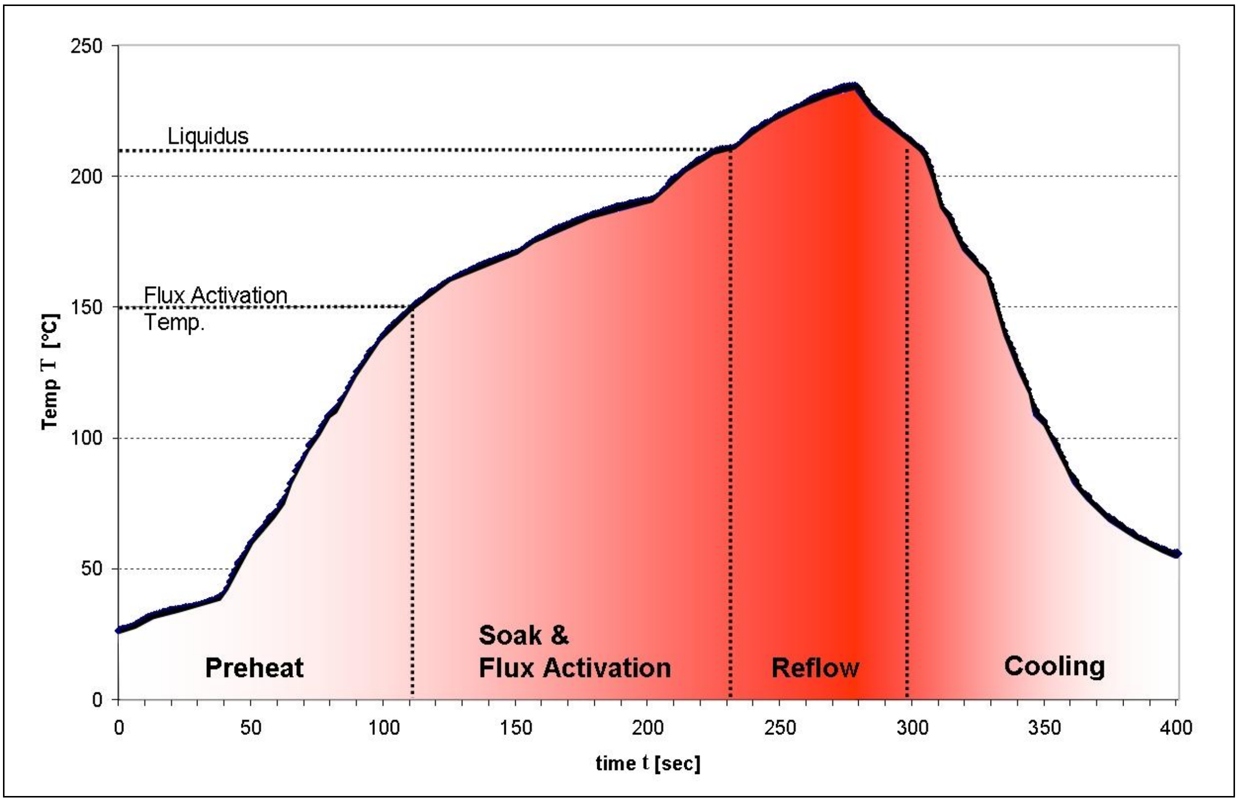


Figure 4: The 4 phases of a reflow soldering profile

The soak period should last for 60-120 seconds, whereas many manufacturers of lead-free solder products specify a maximum of 90 seconds.
The forced convection ovens that are primarily used in the industry provide a more even heat transfer compared to pure infrared ovens. This results in more homogeneous heating of the board, resulting in a more linear heating curve up to the liquidus temperature, depending on the board size, module density and size, and oven efficiency.

P3 Reflow zone

The actual melting and soldering take place in this zone. When reaching the reflow zone, a rise in temperature with a heating rate of about 2 °C/s usually occurs up to the peak temperature. The peak should be 20 °C to 40 °C above the liquidus temperature, which is 217 °C for standard SAC solders. The time above liquidus should be limited to 30-90 seconds to reduce an excessive growth of intermetallic phases and to limit unwanted dissolution effects which can lead to a reduction in solder joint reliability. Remaining too long above liquidus and/or peak temperatures that are too high lead on the one hand to thermal damage, or in extreme cases, charring of the post reflow residue, and on the other hand to damage to the SMD components and the printed circuit board substrate.
In general, it makes sense here to create an initial profile with the recommended values of the solder paste manufacturer and adjust it as necessary to the specifics of the board.

P4 Cool down zone

In the cool down zone, a cooling rate of 3 °C/s should be maintained to allow the components, the printed circuit board, and the solder to cool evenly. This minimizes the stress on the module housing and the solder joints.

Special attention should be paid here to boards with very different coefficients of expansion between component and printed circuit board substrate, such as ceramic-based LEDs and aluminum MCPCB.

Exceeding the permissible cooling gradient leads here to a damage to the components and the substrate.
Likewise, during solidification of the solder, tensions without relaxation can no longer occur.
Cooling that is too slow (≤ 0.5 °C/s), especially at temperatures around the melting point, produces coarser grain structures in the solder, which may affect the reliability of the solder joint and increase the likelihood of a crystalline appearance of the joint (matte appearance).

Summary of the most important parameters of the reflow profile

In accordance with the described sub-division, a reflow profile can be adequately described with the following parameters:

- **Ramp up gradient** divided into two zones, 25 °C – 150 °C and T_{Smax} - T_P
- **Soak time**
- **Time above liquidus T_L**
- **Peak temperature T_P**
- **Ramp down gradient**
- Time at T_{Peak} – 5K
- Special characteristics (gradient jumps)

OSRAM recommendation and maximum permissible values

Although many SMD component manufacturers already offered lead-free components at an early stage and some have completely switched to RoHS-compliant processes since 2002, there still remain questions or difficulties regarding the processing of SMDs in a lead-free process.

To counter the existing uncertainties and the resulting problems, OSRAM Opto Semiconductors presents a detailed recommendation here for the processing of SMD LEDs in the lead-free soldering process. Figure 5 shows the recommended temperature-time profile.
Table 3 also contains a list of the key profile parameters, in which the recommended values represent a suitable initial starting point. These may need to be adapted to the individual needs of the components to be soldered. The specified temperature values always refer to the package peak temperature (PPT).

The gradients in the heating and cooling phases form an equally important parameter for the assessment and evaluation of reflow profiles. The time interval used for the calculation is also decisive.

For an accurate assessment of a profile, it is therefore ultimately necessary to determine the gradient over the entire time.

To determine these gradients, OSRAM Opto Semiconductors used the following calculation.

$$\boxed{\frac{\Delta T}{\Delta t} = Slope \quad (mit\,\Delta t = \max.\,5\sec)}$$

This formula should be used in both the heating (25 °C – T_P) and cooling (T_P – 100 °C) phases.

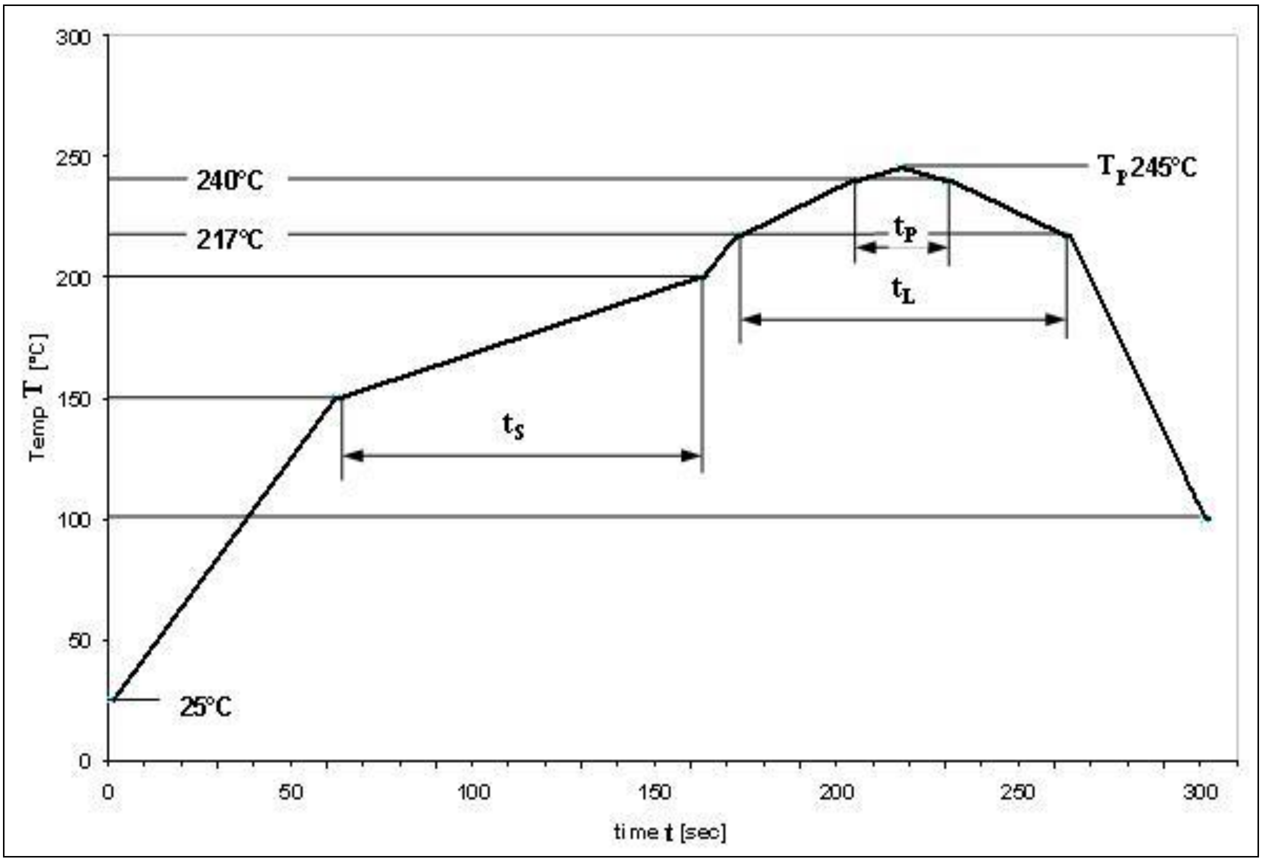


Figure 5 Recommended reflow soldering profile for LEDs from OSRAM Opto Semiconductors

Pb-Free Assembly (SnAgCu)		
Profile Feature	**Recommendation**	**Max. Ratings**
Ramp-Up Rate to Preheat *) 25°C to 150°C	2°C/sec	3°C/sec
Time t_S from T_{Smin} to T_{Smax} (150°C-200°C)	100s	min. 60sec max. 120sec
Ramp-Up Rate to Peak *) T_{Smax} to T_P	2°C/sec	3°C/sec
Liquidus Temperature T_L	217°C	
Time t_L above T_L	80sec	max. 100sec
Peak Temperature T_P	245°C	max. 250°C / 260°C depending on package type
Time t_P within 5°C of the specified peak temperature T_P – 5K	20sec	min. 10sec max. 30sec
Ramp-Down Rate *) T_P to 100°C	3°C/sec	max. 4°C/sec / 6°C/sec depending on package type
Time 25 °C to Peak temperature		max. 8 min.
Notes:	All temperatures refer to the center of the package, measured on the top of the component *) slope calculation ΔT/Δt: Δt max. 5sec; fulfillment for the whole T-range	

Table 3: Profile parameters for recommended reflow process

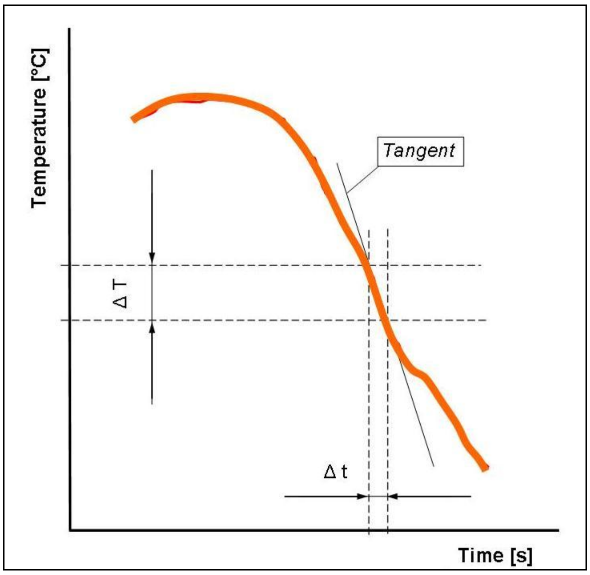


Figure 6: Basis for calculating the gradients for OSRAM Opto Semiconductors

Damage to components caused by the reflow profile and other reflow errors

In many places, commercial demands such as optimized flow line are in the foreground in the creation of the reflow profile, or demands based on subsequent testing processes for the lowest possible output temperature of the boards after the reflow oven.
These demands can usually only be met by relatively high conveyer speeds coupled with higher peak temperatures or extreme cooling gradients in the cooling zone.
Because of this, the allowable thermal stress limits of the components are very often reached or exceeded, leading to possible damage or even spontaneous failure.

Exemplary images of some errors which may result from such a thermal overload of the LEDs are shown below.

Open interface (die-adhesive-lead frame)

A possible error with LEDs is shown in Figure 7. This is caused by a thermo-mechanical overload due to peak temperatures that are too high und extreme cooling gradients.

The thermally induced tension to the LED is so high that the connecting point between lead frame and chip adhesive is torn open.

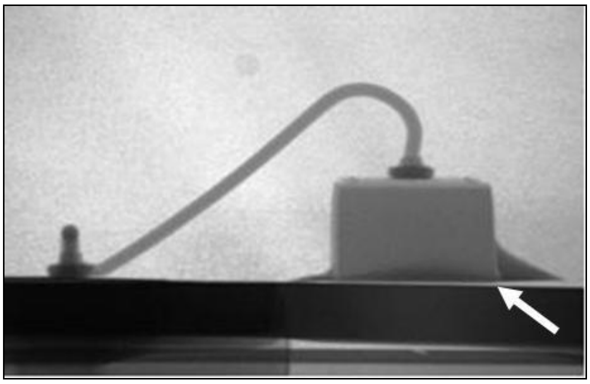


Figure 7: Example of component damage (disruption between lead frame and chip-glue)

In the X-ray image the detached chip including adhesive can be seen clearly.

Crack

"Cobra cracks" may cause the optical characteristics of the LED to be compromised. These cracks in the casting material of the LED are also caused by extreme soldering profiles in combination with components that are processed with a too high moisture content.

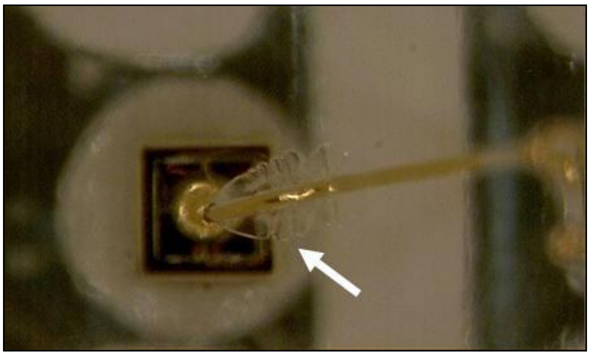


Figure 8: Example of component damage (crack)

Solder errors

A common solder defect, occurring primarily at small, usually two lead or chip components, is known as Tombstoning. Here, due to unbalanced forces on the solder pads during the soldering process, the component is lifted on one side, so that no electrical contact to the solder pads can be formed on one connector pin.

If we compare the two types of profiles, saddle and linear profile, we can see that the error pattern is produced more often in the saddle-type profiles [3]. This can be explained by the much more pronounced transition from the soak phase to the reflow phase (molten phase of the solder) in a saddle-type profile.
In this context we may speak of a jump in the gradient. With this sudden increase in temperature, the risk of damage to the components also increases.
The probability of the tombstone effect is also strongly influenced by other factors such as plant atmosphere (air or nitrogen), transport speed, and the wetting characteristics of the solder pastes that are used, as well as by asymmetrical solder pads. In addition these factors always interact with each other.

For example, a soldering profile is shown below (Fig. 9) that can be used to produce the error patterns described above.

This real measured profile also once again shows the great difference between the temperature measuring point on the solder pad and the measurement on, for example, the component housing. Here, especially, we can see the greatly different cooling gradients.

Both extreme heating and cooling gradients, as well as a pronounced jump in gradient can cause soldering defects and/or excessive thermal stresses that lead to damage of the component.

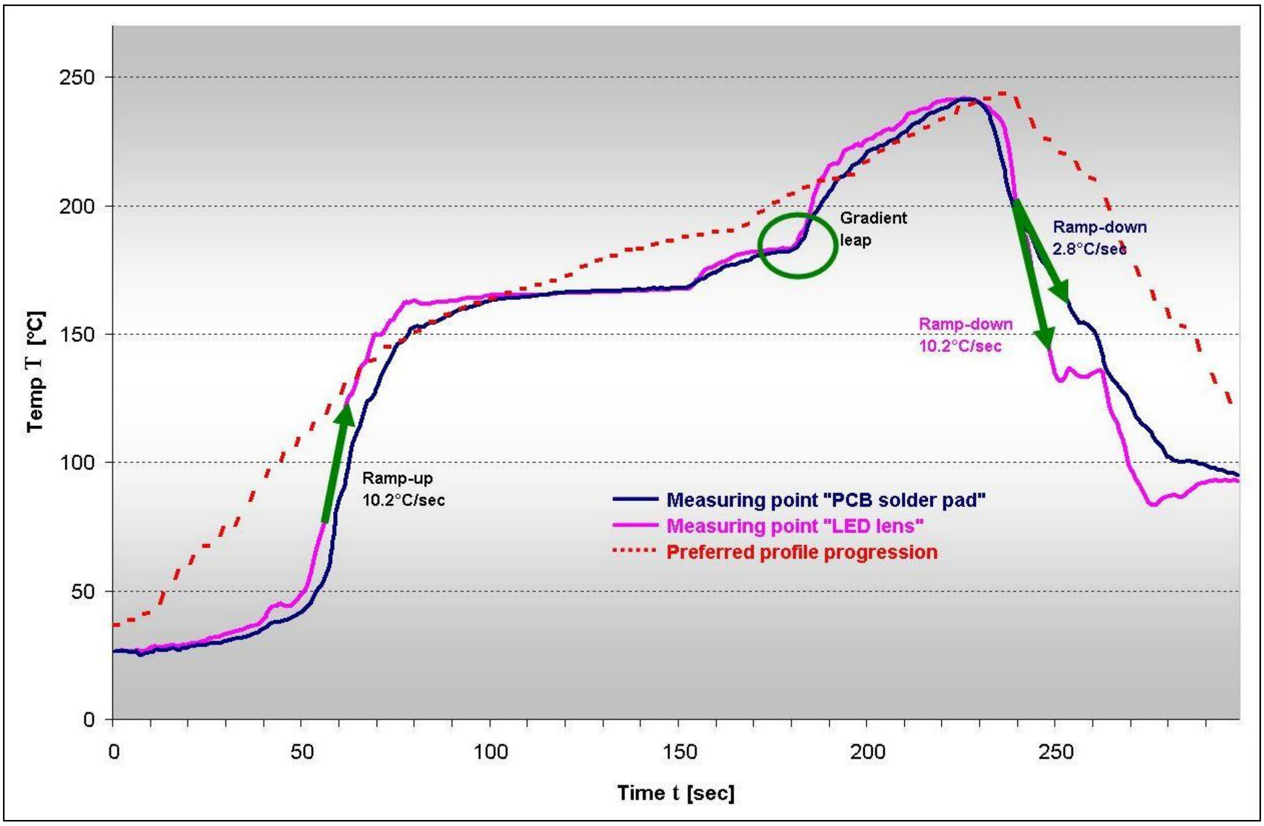


Figure 9: Example of an unsuitable reflow profile with abrupt heating or cooling curve progression and a jump in gradient

Possible measures for optimizing the reflow profile

As described wrongly selected parameters and attitudes can cause a substantial damage of the component to be soldered. The following references should assist and point out possibilities to optimize the reflow profile respectively to realize a LED friendly solder process as possible with few modifications.

- Limit the peak temperature to approx. 240 °C
- Linear heating
- Avoidance of jumps in gradient (transition from soak to reflow zones)
- Uniform curve progression around peak temperature in the time intervall over liquidus temperature (Fig. 10)
- Use of the last heating zone for gentle cooling (approx. 170 °C)
- For active cooling zone: Increasing the operating point of the chiller (generally only possibly by equipment manufacturer)
- Cooling zones: Reduce the fan speed to minimal value
- Reduction of conveyer speed (may require simultaneous temperature adjustment ↓ in all heating zones)

Summary

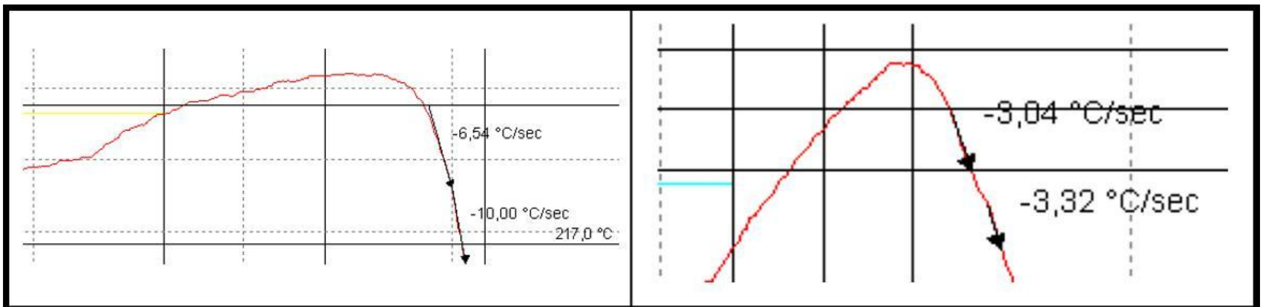
In this publication, the critical parameters for creating a lead-free reflow soldering profile are once again shown and described in detail. It focuses on the prevention of heat-induced damage to the SMD components and PCB substrates that are used.

The recommendations it makes may ultimately represent only a starting point that must always be adapted to the individual circumstances of the boards and the manufacturing environment (oven, etc.).

The increased process requirements of lead-free solder paste with a simultaneously reduced process window also quickly push reflow ovens to their limits. It is therefore necessary to apply all possible technological opportunities of the ovens to achieve the optimum profile setting.

As also described in JEDEC, the limits shown here should be considered absolute upper limits for the values tested in component qualification and should therefore not be used in the manufacturing process.

As shown in many studies and papers [4], an optimized and controlled soldering process is not only a prerequisite for the functional efficiency of a board assembly, but also significantly influences the quality of the solder joint, and thus its reliability.



incompatible curve progression	preferred curve progression

Figure 10: Examples of different curve progression for the period over liquidus temperature

References:

[1] JEDEC J-STD 020 D.1
[2] JEDEC Publication No 140
[3] Dr. Hans Bell, Reflowfehler und Reflowprofile, Rehm Thermal Systems GmbH, September 2007
[4] Dr. Hans Bell, Reflowlöten Grundlagen, Verfahren, Temperaturprofile und Lötfehler, Eugen G. Leuze Verlag Bad Saulgau, ISBN 3-87480-202-7
[5] P. John Shiloh and John Malboeuf, How to Profile a PCB, Novostar Technologies, 2005

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ABOUT OSRAM OPTO SEMICONDUCTORS

OSRAM, Munich, Germany is one of the two leading light manufacturers in the world. Its subsidiary, OSRAM Opto Semiconductors GmbH in Regensburg (Germany), offers its customers solutions based on semiconductor technology for lighting, sensor and visualization applications. Osram Opto Semiconductors has production sites in Regensburg (Germany), Penang (Malaysia) and Wuxi (China). Its headquarters for North America is in Sunnyvale (USA), and for Asia in Hong Kong. Osram Opto Semiconductors also has sales offices throughout the world.
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